IMPROVEMENTS TO THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR: THE DEVELOPMENT OF NEW BONE CORES

Thomas KINSKY, Adam Opel AG / General Motors Europe Engineering, Germany[*)]
Martin FRITZ, 4a Engineering GmbH, Austria
Peter LESSMANN, BGS Boehme and Gehring GmbH, Germany
Franz ROTH, AUDI AG, Germany[*)]

[*)] representing the Task Force Pedestrians of the European Automobile Manufacturers' Association (ACEA)

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ABSTRACT

During the first decade of the 21st century, pedestrian safety in general was one of the main subjects of vehicle safety development. For the legform testing, the impactor developed by the European Enhanced Vehicle-Safety Committee was the standard impactor but experts from Japan introduced a new impactor, the so-called Flexible Pedestrian Legform Impactor (FlexPLI). The FlexPLI is capable to quantify the load of a human long bone, which is a significant advantage when developing vehicles with reduced bone fracture risk.

With the impactor being developed by a single company spare part availability was limited. In addition, potential improvement in terms of robustness in maximum load were identified. Therefore, a joint project was initiated, in which automobile manufacturers and their partners developed universal spare parts for the FlexPLI bone cores. These parts can withstand higher bending loads, are available from stock and do not need to be adapted to a specific legform. Furthermore, a reduction in variation of properties due to a different production process was achieved. This reduces performance variation within the legs and is comparable to the initial bone core mean performance. The document introduces the details of the project.

INTRODUCTION

During the first decade of the 21st century, pedestrian safety in general was one of the main subjects of vehicle safety development. For the legform testing, the legform impactor developed by the working groups of the European Enhanced Vehicle Safety Committee (EEVC) was state of the art at that time. However, to enhance the representation of a true human leg, experts from Japan introduced a new legform impactor when others still tried to understand how to work with EEVC Legform Impactor (EEVC LFI).

The new Japanese impactor, nowadays called Flexible Pedestrian Legform Impactor (FlexPLI), provides one significant advantage compared to the EEVC LFI: In addition to the assessment of knee injuries, it is able to also assess injury risks to the long bones of a human leg.

To promote the introduction of the new legform and to allow experts of other regions also contributing to the development, the Japan Automobile Research Institute (JARI) and the Japan Automobile Manufacturers Association (JAMA) lend different build levels of the impactor to labs outside Japan.

The European Automobile Manufacturers' Association (ACEA) was equipped with several FlexPLI's by Japan for several years. This allowed ACEA members to conduct tests at different labs such as Concept Technologie GmbH in Austria (Concept), the Bundesanstalt fuer Strassenwesen / Federal Highway Safety Research Institute (BASt) and BGS Boehme and Gehring GmbH[1] as well as Bertrandt Ingenieurbuero GmbH (Bertrandt) in Germany. During those tests, learnings and expertise were generated. These were brought into the activities of the UNECE Informal Group on Pedestrian Safety (INF GR PS) (working from 2002 to 2006), the UNECE Technical Evaluation Group (TEG) (working from 2005 to 2010) as well as the UNECE Informal Group on gtr No. 9 – Phase 2 (IG GTR9-PH2) (working from 2011 to 2013).

[1] BGS Boehme und Gehring GmbH is the company operating the test laboratory of the German Bundesanstalt fuer Strassenwesen / Federal Highway Safety Research Institute (BASt).

Finally, the efforts of the working groups mentioned before led to the introduction of the FlexPLI into UN Regulation 127 as of January 2015 as well as to a corresponding draft amendment for the gtr No. 9, which is in the process of adoption. The design of the FlexPLI has achieved a build level that will allow its future use for regulatory purposes. However, room for further improvements to this build level is seen and one of the respective solutions is presented in this document.

CONCERNS WITH THE DESIGN OF THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR

During one of the first test series conducted on behalf of ACEA by the company Concept in 2004, Knotz reported about concerns with the – at that time too low – stiffness of the FlexPLI. Knotz tested an early version, the version 2003, of the new impactor. He noted that the legform had a tendency to bend extremely and to follow the contour of the tested vehicles (Knotz 2004, page 25). Experts of ACEA members raised the concern whether this could result in damages to the bone cores of the FlexPLI and whether this indeed represents the behavior of a human leg.

From their testing with the next generation of the FlexPLI, the version 2004, Mallory, Stammen and Legault reported about damages to the bone cores of the impactor in three out of five tests (Mallory, Stammen, Legault 2005, page 8).

Feedback generated in such tests lead to one major design change that was introduced in 2005 with the FlexPLI version G: Starting with this version, all FlexPLIs have a squared design of tibia and femur sections, compared to the round tibias and femurs of the earlier versions. In the corners of the respective sections, steel cables are placed to limit the maximum bending of tibia and femur and therefore prevent the impactor from being excessively bent.

Figure 1 shows a principal drawing of the latest build level of the new impactor. "The FlexPLI consists of a femur and a tibia, which are composed of bone cores made of fiber glass, and several nylon segments attached to them. The overall design of femur and tibia represents the human bones and their ability to be bent. Strain gauges, glued to the fiber glass core, are used to measure the bending moments at the different segments and thereby assess the risk of bone fractures. The knee element consists of two complex blocks, where string potentiometers represent the human knee ligaments. Their elongations assess the risk of ligament injuries… Human skin and flesh are formed by several layers of rubber and neoprene sheets. To closer follow the geometry of a human leg, the number of layers is different for femur, knee and tibia…" (Kinsky, Friesen, Buenger 2011, page 2ff.)

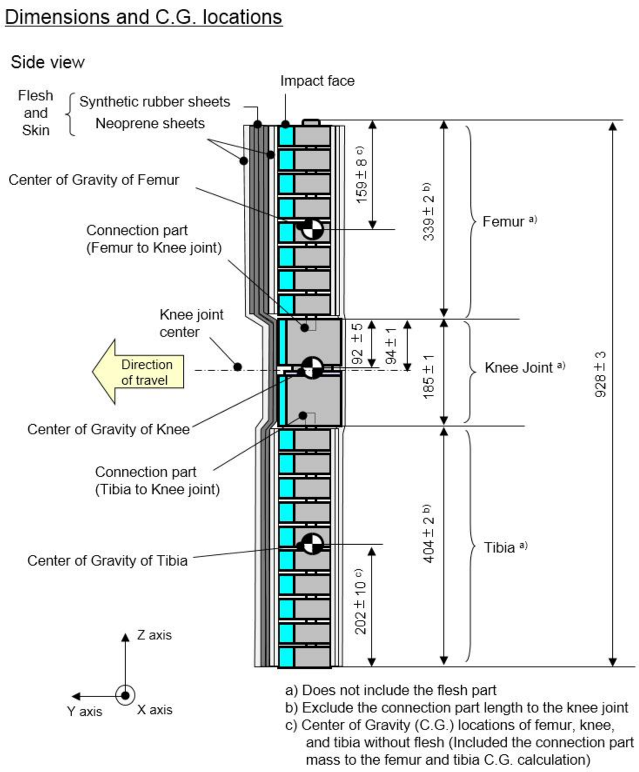

Figure 1: Latest design of the FlexPLI as introduced in the 01 series of amendments to UN R127 (UNECE 2015, page 26)

In 2008, Been and colleagues summarized the development status of the FlexPLI in its intended final version GTR[2] (Been et al. 2008). Been and colleagues introduced the 3-point quasi-static bending test applied to the bone cores individually as well as to the total assemblies to prove the material robustness. This test was carried into calibration and certification procedure of the assemblies for official impact tests. However, in all these tests the bone cores were, by that time, never loaded with bending moments of more than 400 Nm – moments, which could be expected frequently when considering that the maximum bending moments in discussion at that time were in this range. Been et al. also explained that the plastic material surrounding the glass fibers was changed at that time from polyester to vinylester to improve the durability (Been et al. 2008, page 34) and that the old and the new bone core material had been overload-tested with bending moments of 500 Nm to prove the optimization (Been et al. 2008, pages 35ff.). However, experts from ACEA members felt that this still will not be sufficient for development tests were the initial performance of new cars may still to be quantified.

In 2011, Kinsky reported on a first long-time durability assessment with one of the prototypes of the FlexPLI version GTR (Kinsky 2011). Kinsky noted significant wear and visible white cracks on the surface of the bone cores by matrix failure in the bone core material (Kinsky 2011, pages 13 ff.). The report raised also concerns about the availability of spare parts for the impactor.

Additionally, experts of Humanetics, producing the FlexPLI version GTR, stated in 2011 that the fiberglass bone cores are tailor-made for each single legform (Humanetcis 2011). This was explained with the production process of the fiberglass material that cannot guarantee stable material properties. The material is produced in a pultrusion process as a straight profile (see figure 2). Since, according to Humanetics, the glass fibers are not necessarily orientated in line and the thickness of the profile is reduced by machining by about one third, the final batch of material has varying quality (high variation of strength and stiffness). Therefore, the bone cores are produced as blanks and then are slightly reworked to fine-tune the performance in the tibia and femur assemblies. According to the drawings, the bone cores finally vary in thicknesses between 10.3 and 10.9 mm (Humanetics 2015), which in principle makes each bone being unique. Also, the experts of Humanetics stated that the ultimate strength of the straight profile is foreseen for a maximum of 250 MPa (which approximately corresponds to a bending moment of 185 Nm) but that Humanetics tested them up to 400 Nm bending moment (which would require a minimum strength of 540 MPa)

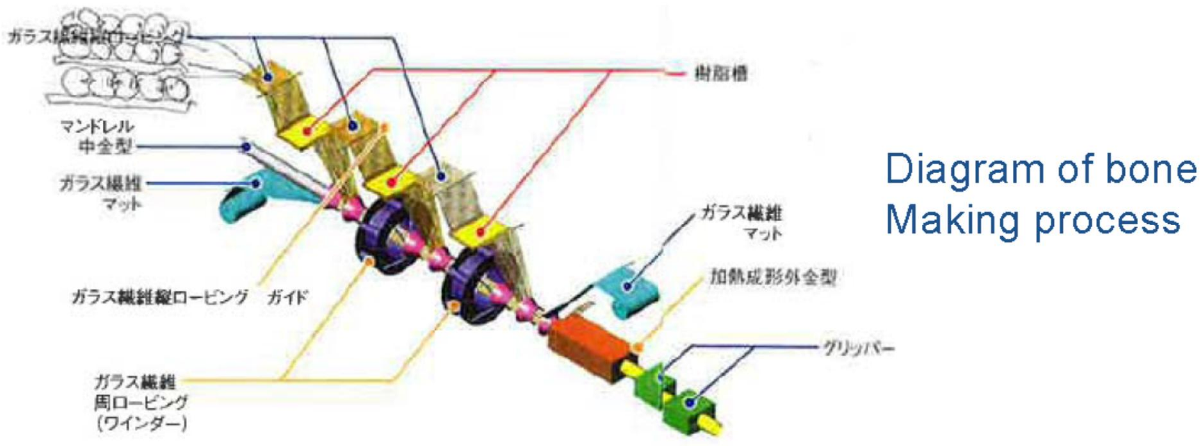

Figure 2: Diagram of the production process for the bone core material, which is then processed in several further steps to the tailor-made bone core for each FlexPLI (Humanetics 2011, page 21)

Based on the statements of Humanetics, concerns were raised by automobile industry experts: Will the FlexPLI withstand higher loads then the legislation limits, also if these loads occur more than once? Will spare parts be available on short notice? How can the required impactor’s finite elements (FE) model address variation of the actual parts? Etc.

[2] Early versions of the FlexPLI had been named according to their year of introduction. Since 2005, the new versions were named G, then GT and finally GTR, indicating that the development steps should lead to the use in the global technical regulation (gtr) on pedestrian safety.

DEVELOPMENT OF NEW BONE CORES FOR THE FLEXPLI

Experts of ACEA finally decided to support enabling alternative suppliers of the bone cores. The product specifications included:

- The new bone cores should have the ability to withstand bending moments of at least 20 percent above the limits foreseen for legislation (with legislation limits still being in final discussion at that time);
- The material behavior should be reproducible with just small variations in the product performance;
- The dimensions of the new bone cores should fit the dimensions of the other parts of the FlexPLI to avoid a need of further modifications to the impactor;
- The new bone cores should preferably be available as spare parts on stock, without a need to fine-tune them for their use in a specific legform impactor;
- The new bone cores should allow for the use of the different data acquisition systems already in use by different ACEA members;
- A material model should be made available for the simulation;
- Further improvements to the bone cores as well as to the whole FlexPLI could be discussed, if possible.

A preceding project on this topic had been conducted by Partnership for Dummy Technology and Biomechanics (pdb) in Ingolstadt/Germany and Adam Opel AG in Ruesselsheim/Germany with the company 4a Engineering GmbH (4a) in Traboch/Austria. Therefore, ACEA decided for a joint project also with 4a. 4a is a technically oriented research and development company with the focus on plastics engineering and composite material science. They choose to cooperate with the well-experienced test labs BGS in Bergisch Gladbach/Germany and partially also with Bertrandt in Gaimersheim (near Ingolstadt)/Germany. Both labs were experienced in testing the FlexPLI. BGS conducted tests with all earlier versions of the FlexPLI since 2004 and contributed to joint projects with ACEA aiming to improve the impactor. Bertrandt was one of the very first owners of the latest FlexPLI version in Europe and conducted many tests with this version that also helped to improve the design.

After an initial assessment, following objectives were defined for 4a to achieve: The bone cores should be made of a new composite material with narrow variation of the material properties. The fiber matrix combination in this material should be optimized for maximum fatigue strength. Also, the cross section and the bending behavior should be optimized compared to the original bone cores. Finally, 4a also suggested using an improved fixation concept for the bones, taking into account the anisotropy of the material.

In a first step, 4a sourced a new fiberglass material for the bones. The new material is specifically produced for the purposes of the legform impactor with a thickness very close to the final dimensions of the bone cores. Then, the surfaces are grinded down just a few tenth of a millimeter to have flat surfaces that allow the attachment of the strain gauges. The new material has a bending strength of at least 750 MPa (corresponding to 550 Nm bending moment), compared to 250 MPa of the original part as mentioned before. Also, 4a guarantees that the new bone cores are produced with very narrow production tolerances while having the specified material properties.

The strain gauges are bonded to the front and rear surfaces of the bone cores. Initially, the concept of using wires for each single strain gauge was maintained. However, during the frequent assembling and disassembling of the bone cores during the project it was noted, that the wiring always causes a risk of failure due to pinching, braking etc. 4a therefore finally developed folia-printed flexible circuit boards (PCB's) that are attached to the bone core surfaces and that allow minimized wiring. Just one wire per PCB is needed that is placed on the non-struck side close to the knee element.

Using the PCB's also solved issues with the electrical resistance, specifically the bridge resistors. It was observed that in some cases Wheatstone bridges for the strain gauges were also fitted to the data logger board, in addition to resistors in the plugs. The respective wiring depended on the data acquisition system and was impactor specific. Therefore, in these cases the sensors could not be calibrated without the data acquisition system. This would have created issues when producing the bone cores as universal spare parts. The PCB now allows placing all bridge resistors on the PCB, independent of the data logger or the plugs used. Of course, affected FlexPLIs need to be modified accordingly in the beginning but this finally guarantees easy supply of spare parts.

Finally, the bones are covered by heat-shrink tubes. This guarantees the proper dimensions of the bone cores while, at the same time, protecting the strain gauges and the PCB's as well as the bone cores' surfaces from external damaging.

To attach the bone cores to the FlexPLI knee, 4a developed new clamps. Those clamps make contact over the full width of the bone core – in contradiction to the original ones that just contact the bones locally. Due to this, seating stress can be significantly reduced and much higher clamping forces can be achieved.

Figure 3 shows the two major parts as well as the final assemblies of the 4a bone core spare parts (see figure 3). The parts have the same attachment dimensions as the original parts and the same mass, they have a similar test performance, but they provide a better robustness and durability. However, especially the latter details needed to be proven by tests.

Figure 3: Final assembly of 4a femur bone core and 4a tibia bone core spare part, the PCB for a tibia as well as a tibia blank (from left to right) (photograph: 4a Engineering GmbH)

COMPARISON TESTS WITH THE NEW BONE CORES

During the development of the new bone cores, numerous tests had been conducted at BASt by BGS as well as by Bertrandt. The final tests confirming the usability were conducted by BGS. Besides the FlexPLI certification tests on component as well as on assembly level, the project partners decided to conduct tests against a test rig that was configured to represent a sedan-type vehicle. The test rig is a standard test rig that had been developed for validation purposes and was also used for other ACEA projects.

For the certification, quasi-static bending tests of the bone cores for sensor calibrate, certification tests of tibia, femur and knee assemblies as well as final certification tests of the complete legform impactor, have to be conducted. All tests were passed without issues using three different impactors. These three impactors were equipped with three different data acquisition systems. For the certification of the impactor, both tests configurations as foreseen in the UN R127 were conducted: the so-called pendulum testing as well as the so-called inverse testing.

Also, BGS conducted tests against the test rig that was designed to represent the typical load paths of a sedan-type passenger car (see figure 4). During these tests, no unexpected results were achieved and testing proceeded without any noticeable problems.

The test results from the certification tests and against the test rig are shown in annexes 1 to 3. Observed differences in elongation values of the knee are not influenced by long bones and are impactor specific since the knee section of the different impactors had not been modified.

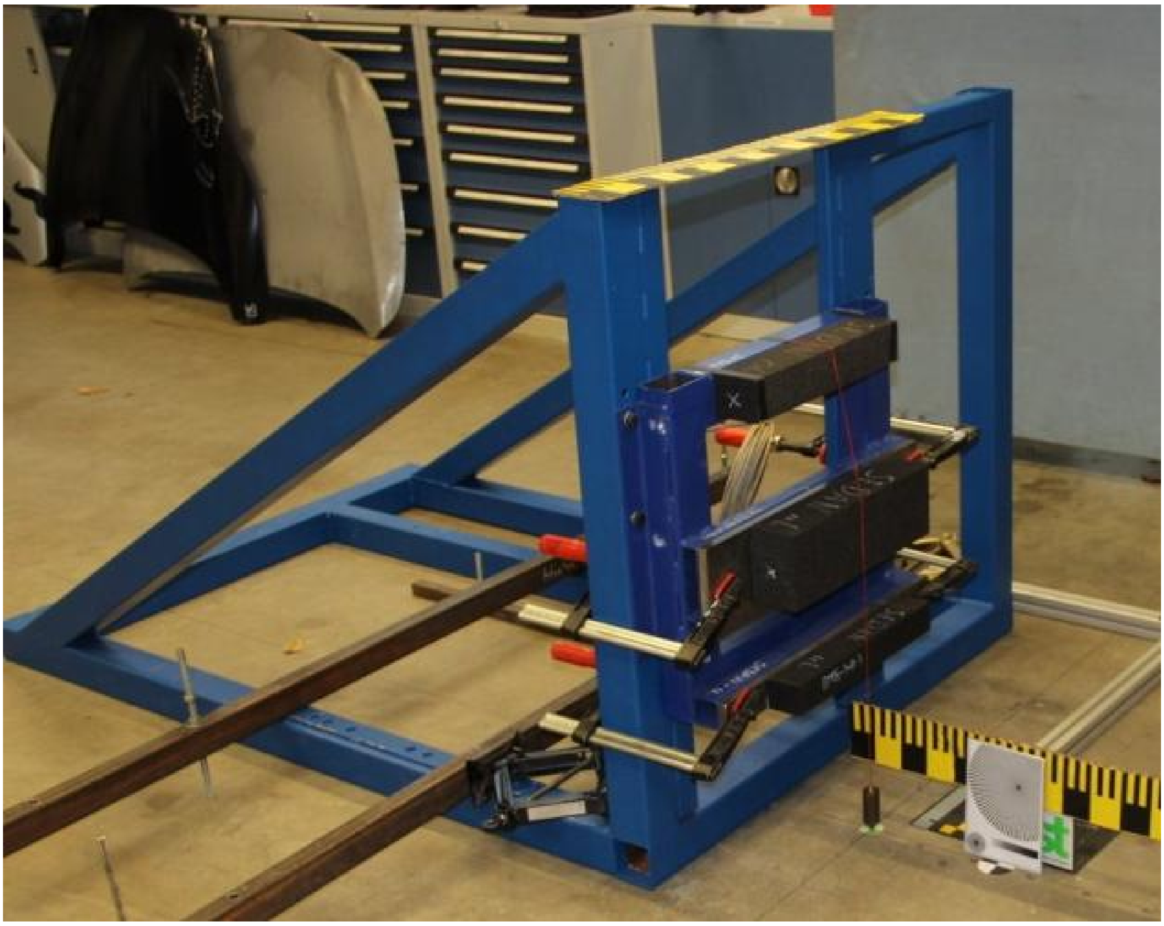

Figure 4: Test rig representing the typical load paths of a sedan-type passenger car (photograph: BASt/BGS Boehme and Gehring GmbH)

After finalizing the tests described above, two further impactors have been equipped with the new 4a bone cores. In addition, these impactors work properly without any abnormalities. After evaluating the data generated in the tests, the project partners finally concluded that the new spare parts can be made available for industrial use.

REMAINING ISSUES

One major issue coming up during the activities described above were the connector plugs used for the data acquisition systems (including the wiring) of the different legforms. These plugs were observed to be not suitable for the usage in such an impactor and are subject to frequent failure (breakages of the plugs, breakage of the strain relief, disconnections during the acceleration of the impactor, etc.). In addition, these plugs are uncommon (at least in Europe) and acquiring spare parts turned out to be a serious challenge due to limited availability. Therefore, future users of the new 4a bone cores are recommended to also replace the connector plugs to ensure availability of the test tool for vehicle development. Substitution of the Wheatstone bridges may need additional efforts in the beginning but it ensures an uncomplicated and easy supply of spare parts afterwards.

In addition, the project partners noted that several further improvements to the FlexPLI may be possible, aiming at the improvement of the handling, the durability and the robustness of the whole impactor. It was therefore decided to further investigate possible improvements to the impactor in new projects.

Finally, further steps will be needed to develop the FE model of the FlexPLI. Currently, no validated model exists. As soon as this issue is solved, the new 4a bone cores will need to also be provided as supplements to this model. However, from the project team no further issues are expected with this.

CONCLUSIONS

In this joint project, ACEA together with 4a, BGS, Bertrandt as well as pdb developed universal spare parts for the FlexPLI bone cores. These parts can withstand higher bending loads than the original bone cores and have no influence on the certification output. They are available from stock and there is no need for legform-specific adaptations. In addition, the new parts are produced with higher accuracy so that no variation of their performance needs to be expected. Some further improvements to the electric equipment of the impactor as described above will allow the universal usage of the new bone cores.

ACKNOWLEDGEMENTS

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FREQUENTLY USED ABBREVIATIONS

ACEA	European Automobile Manufacturers' Association
EEVC	European Enhanced Vehicle-Safety Committee [originally founded as European Experimental Vehicle Committee]
FE	finite element
ff.	and the following
FlexPLI	Flexible Pedestrian Legform Impactor
JAMA	Japan Automobile Manufacturers Association
JARI	Japan Automobile Research Institute
LFI	Legform Impactor
PCB	printed circuit boardUNECE United Nations Economic Commission for Europe

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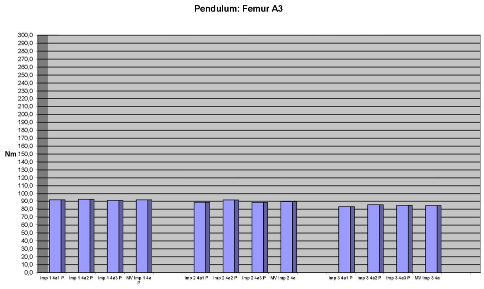
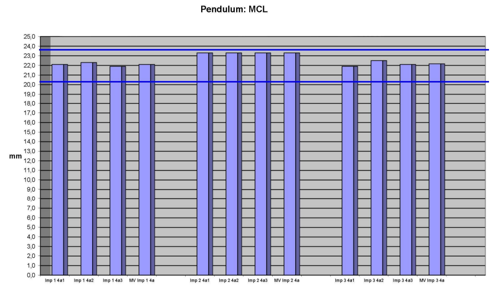
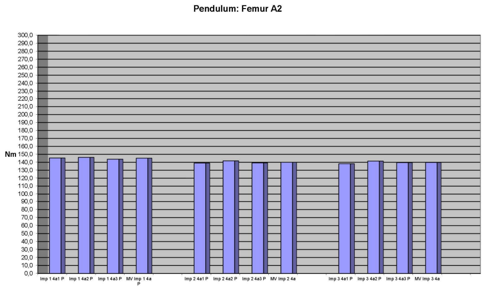
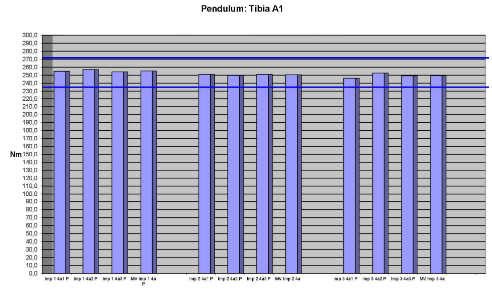
ANNEX 1 – TEST RESULTS PENDULUM CERTIFICATION

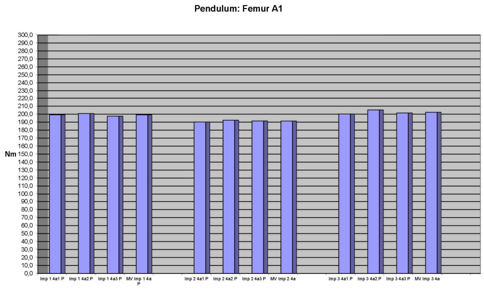
Test results for 3 different legforms with 3 repetitions each, the most right bar in each block represents the mean value.

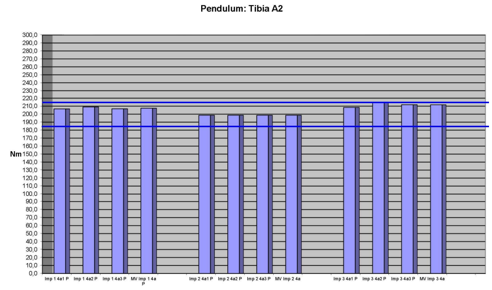


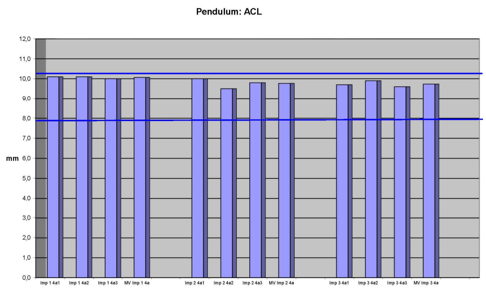


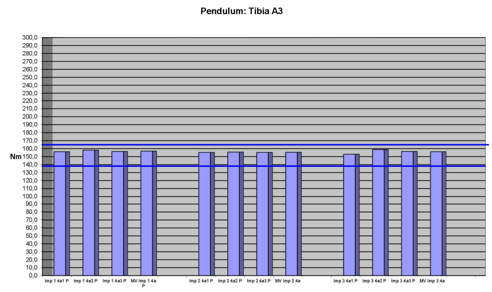


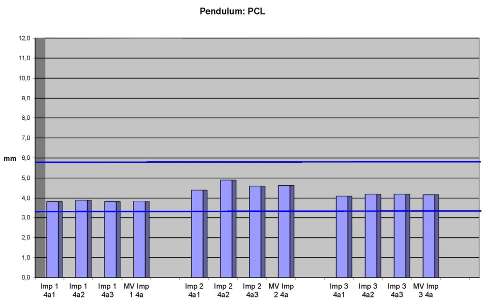


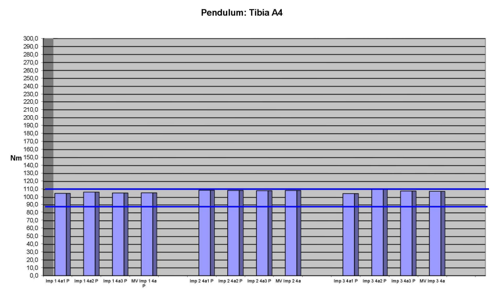






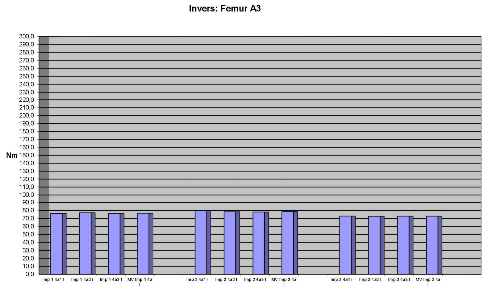


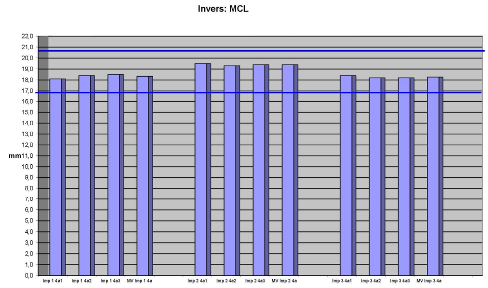


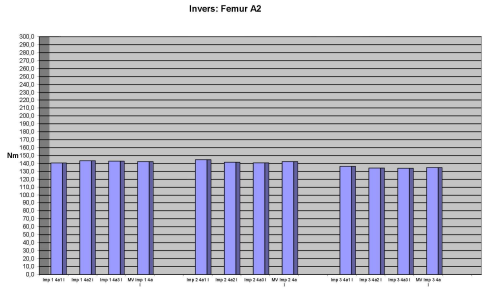


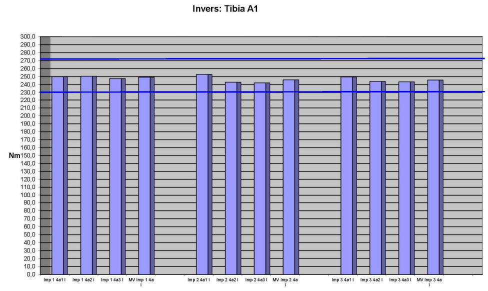
ANNEX 2 – TEST RESULTS INVERSE CERTIFICATION

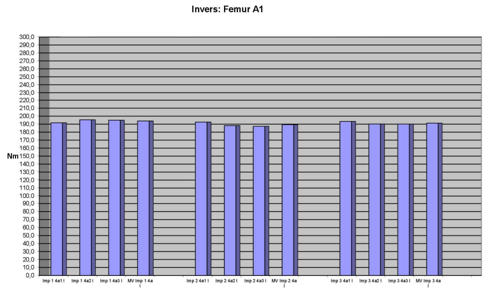
Test results for 3 different legforms with 3 repetitions each, the most right bar in each block represents the mean value.

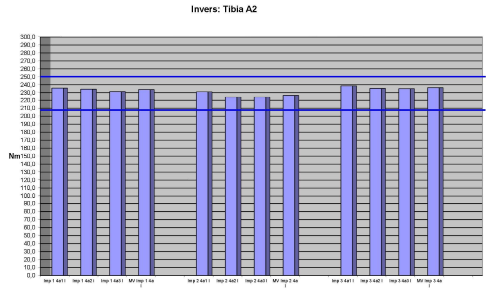


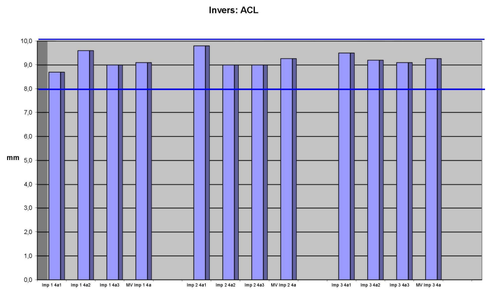


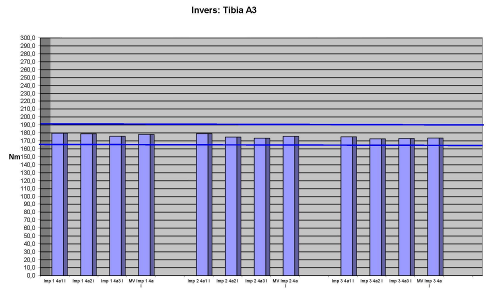


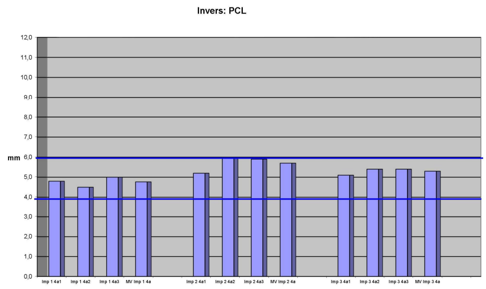


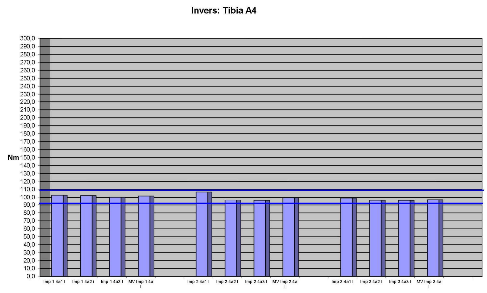












ANNEX 3 – TEST RESULTS SEDAN TEST FRAME

Test results for 3 different legforms equipped with 4 a bone cores with 3 repetitions each (left blocks in each diagram), in comparison with 3 legforms equipped with the original bone cores (right blocks). The most right bar in each block represents the mean value.